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REVIEW

IMPROVING NITROGEN SAFETY IN CHINA: NITROGEN FLOWS, POLLUTION AND CONTROL

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KEYWORDS

barriers, future management, ammonia emissions, nitrogen input, water N pollution

HIGHLIGHTS

- It is necessary to address the N flows and their impacts on environment in China for sustainable N management.
- Barriers include better understanding of N cycle mechanisms and improving low cost abatement technologies are needed to overcome.
- Integrated measures and policies are crucial for the abatement of adverse impacts of N.

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GRAPHICAL ABSTRACT

ABSTRACT

The impacts of nitrogen on environmental quality, greenhouse gas balances, ecosystem and biodiversity in China are of great concern given the magnitude of demand for food and energy. Comprehensive summaries of historic N flows and their critical threats and sustainable management are urgently needed. This paper initially reviews the historical trends of N flows in China and identifies the critical threats of N loss. Subsequently, it describes some recent success stories of N management, and finally indicates barriers to N pollution control. This review highlights three key points. Firstly, a steady increase of N input in China has led to a series of environmental problems via leaching and runoff, ammonia emissions and denitrification. Secondly, although great efforts to improve N management and N safety in China, further quantifications of N flows and analysis of their underlying mechanisms are needed to improve the understanding of the N cycle and pollution control. Finally, it proposes that the best available technologies combined with regulatory plans, laws, projects and policies should be implemented to overcome current barriers in N control and achieve a balance between the sustainable use of N resources and environmental conservation in China.

1 INTRODUCTION

Nitrogen is a crucial nutrient required by all forms of life for survival on Earth. Globally, human activities produced 226 $\mathrm{Tg \cdot yr^{-1}}$ N during 2020, which was three to four times greater than the natural terrestrial biological N fixation rate[1]. Although N input can increase agricultural production, excess N use causes various environmental problems from local to global scales. The contributions of excessive N to grain security, environmental and health issues, global climate change, biodiversity loss and the degradation of ecosystem services have already been widely documented[2–5].

Feeding and fueling its large population and industries while preserving the environment is also a long-standing challenge for China. Since the launch of the reform and opening-up policy in the late 1970s, China has experienced rapid economic growth. China's agriculture sector has made notable achievements in the world. China has succeeded in producing about a quarter of world grain and feeding a fifth of the global population, with only 9% of the global arable land. The increased use of mineral fertilizer N has had a vital role; China consumes about 30% of the global anthropogenic N and total N input in China increased from 24.7 Tg in 1980 to 85.5 Tg in 2017[6,7].

Although fertilizer N increases crop yields and protein production, low N use efficiency (NUE) results in a large amount of N lost into the environment, which causes various environmental challenges and ecological, socioeconomic, and health consequences in China and beyond[8–12]. Consequently, significant effort has been spent to improve N management with the purpose of balancing the sustainable use of N resources and environmental conservation in China. For example, scientific research regarding N fluxes, their impacts on ecological pollution and abatement has been conducted in China[10,11,13–16]. In addition, China's funding agencies (e.g., the National Natural Science Foundation of China and the Ministry of Science and Technology of China) have launched several programs to investigate scientific questions, such as N assessment, pollution and control. In addition, the Chinese Ministry of Agriculture and Rural Affairs proposed a zero-increase action plan for fertilizer use by 2020 in 2015[17]. Significant progress regarding N management has been made in China by implementing policies, regulations and scientific research. For example, NO_x emissions in China decreased following the implementation of the national NO_x total emission control policy in 2010[18]. Also, based on the implemented programs, regulations and plans, such as zero fertilizer growth, soil testing and fertilizer recommendations, the NUE of three major crops, wheat, rice and maize, increased from 28% to 33% during 2005–2013[19].

Great achievements regarding N management and pollution control have been made in the past 10 years, however, future N use and management still face challenges with the increasing population and food demand in China. Hence, this paper presents N flows and pollution threads in China and introduces the progress in regards to N management over the past decade. This article also illustrates major barriers to current N management and recommends strategies and policies for future N control.

2 NITROGEN FLOWS AND POLLUTION IN CHINA

2.1 Analysis of N flows

With the rapid development of the economy and population from 1980 to 2018 in China, total N sources, including chemical fertilizer, biological N fixation and N deposition increased from 24.8 to 68.4 Tg N[20]. Biological N fixation was a relatively small input source, while mineral fertilizer N application dominated N input by the sharply increasing of Haber-Bosch industry. Over the past half-century, agricultural mineral N applications have increased more than 48-fold in China[21]. Most of the mineral fertilizer N was applied to arable land to maintain crop production despite agricultural fertilizer N use increasing from 2005 to 2014 (Fig. 1). In addition, as one of the important sources of N input, N deposition increased from 2.85 to 19.60 Tg during 1961–2015[22,23].

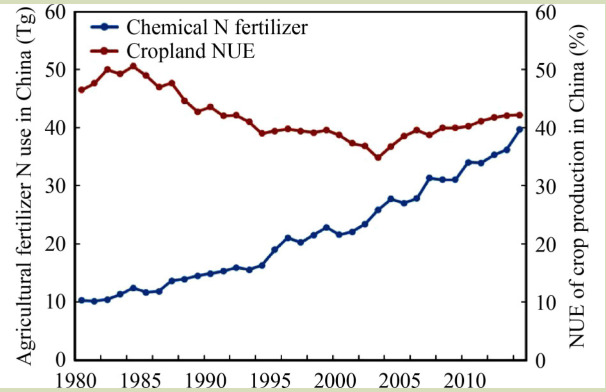

Fig. 1 Agricultural fertilizer N use and NUE in China from 1980 to 2014.

Total N input may increase in the future owing to more intensive anthropogenic activities[1]. However, large proportions of N input are lost to the environment due to overuse and unsuitable management practices. The cropland system is an example. Crop yields have increased from 9.34 Mt in 1980 to 19.3 Mt in 2019 by applying N fertilizer as a primary nutrient source in China[24]. However, our recent study indicated that the NUE for crop production in China increased from 47% in 1980 to 51% in 1984 and then decreased gradually to a recent minimum of 35% in 2003 (Fig. 1); thereafter, it increased steadily to 42% in 2014[25]. Also, except for cropland NUE, the NUE of systems such as livestock and grassland was lower than 25% during this period[20].

More than half of the total N input was lost to the environment. The loss of N almost doubled from 1980 to 2018, far exceeding the growth rate on a global scale[26]. Excess N losses via NH_3 emissions and denitrification were the largest contributors to N loss, followed by N leaching and runoff from cropland and wastewater treatment. According to Zhang et al.[20], N loss in 2018 through leaching, runoff, and gaseous emissions (including NH_3, NO_x, N_2O and N_2) were 5.3, 10.2 and 50.3 Tg, respectively. In addition, the difference between the N input and output results in terrestrial ecosystem accumulation. Accumulated N is an important pool in the global system and has a wide variety of consequences, such as a cascade of environmental pollution. Overall, except for the temporal variation in N flow, there were significant spatial changes across China. Results showed that N input and loss hotspots sporadically occurred in areas such as the Middle-Lower Yangtze River Plain, North China Plain and Sichuan Basin. In contrast, N input and loss intensity were lower in western and north-eastern China[7,27]. Factors such as human population density, land use type and per capita gross domestic product impact spatial variations in N budgets[13]. In addition, there have been several studies regarding China's N flow and budget over the same period. However, the assessment results differ because of the different methodologies or parameters/databases used[6,13,28].

2.2 Key N threats

Although N is a major contributor to the increase in food and fuel production, excessive use of N has been reported as a key threat to the environment and human health because the denitrification rate does not maintain the N creation rate[1,29]. Scientists divided N threats into five areas: WAGES[30], which stands for water quality, air quality, greenhouse gas balances, ecosystem and biodiversity, and soil quality (Fig. 2). Here, we introduce how N affects WAGES in China.

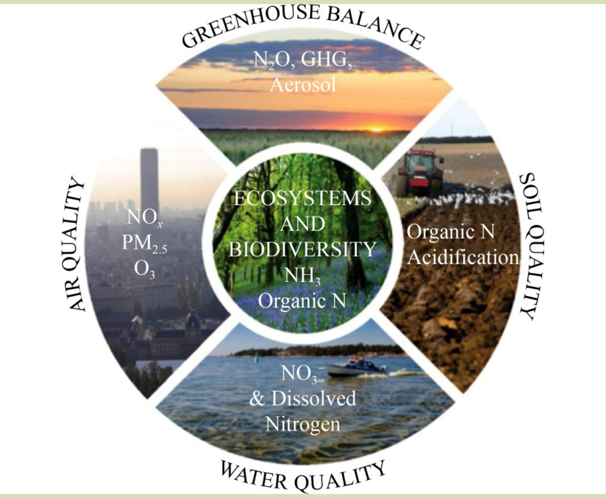

Fig. 2 The five key threats of excess reactive N. Sourced from Sutton et al.[30], with permission from Cambridge University Press.

Surface water pollution is mainly driven by N. About 18% to 21% of the total input N is exported to water bodies according to Ti et al.[13]. Hence, many Chinese lakes and rivers are eutrophic due to excessive N. For example, Taihu Lake, the third-largest freshwater lake in south-eastern China, has been experiencing eutrophication and frequent algae blooms since 1987[31]. In May 2007, a severe algal bloom in Taihu Lake resulted in a drinking water crisis, affecting the drinking water supply of about 2 million people in Wuxi, China[32]. The annual average total N (TN) concentration has been greater than 1.50 $mg \cdot L^{-1}$ during the past 30 years. The local government has introduced stricter laws, plans and guidelines to improve water quality. However, the annual TN concentration reached Grade IV surface water quality in 2018[33]. Similarly, Dianchi Lake, the sixth largest freshwater lake in China, has also experienced water quality degradation over the past 40 years due to its high N concentration[34]. Also, excessive N leaching results in groundwater contamination in China. According to Gu et al.[35], nitrate in 28% of the tested groundwater exceeded the WHO maximum contaminant level (10 $mg \cdot L^{-1}$ N).

The N released into the atmosphere in the form of NH_3, NO_x and N_2O may contribute to the formation of aerosols, dry and wet deposition, global warming and ozone depletion. For example, the total $PM_{2.5}$ doubled from 12% in winter 2014–2015 to 25% in winter 2018–2019 in the North China Plain, a region with severe haze pollution, which is attributed to high concentrations of NO_x and NH_3 combined with volatile organic compounds and SO_2 emitted from regional agricultural and industrial activities[15,36]. In addition, a recent study showed 47% and 74% reductions in agricultural NH_3 emissions, and the annual $PM_{2.5}$ concentration decreased from 43 to 28 $\mu g \cdot m^{-3}$[37]. Also, the contribution of N precursors to acid deposition can alter the structure and function of ecosystems. About 15% of the land over China experiences N critical load exceedances that originate from emissions of NO_x and NH_3[11]. Also, N emissions significantly affect the global climate system. As a key source of non-CO_2 GHG (Greenhouse Gas), analyses have shown that the global-scale warming effect of China's cropland N_2O emissions dominates the local cooling effects ascribed to its NH_3 and NO_x emissions[38].

Soil acidification is another problem in China. A significant decrease in soil pH has been reported in Chinese croplands in response to the over-application of N fertilizer[8,39]. A recent study indicated that the topsoil pH shift of croplands was closely associated with the N fertilizer application rate in central China from 2008 to 2018[40]. Soil acidification increases the risk of yield loss and food insecurity. According to Zhu et al.[41], the expected crop yield losses will be range from 4% to 24% during 2010–2050 by an average soil pH decline of about one unit. Also, it has been reported that excessive N addition to the environment threatens biodiversity[42,43]. N deposition significantly reduced plant species richness and evenness in a meta-analysis in China[44].

Overloading of N in the environment is becoming a serious threat to human health. Compounds react with particles in air to breathe and damage human health. For example, the emitted NO_x promotes the formation of ozone and has adverse health effects on humans by inducing lung cancer and respiratory diseases. According to Lu et al.[45], the total NO_x emission sources are estimated to cause 2119 respiratory deaths and 991lung cancer deaths due to long-term exposure to NO_x in the Pearl River Delta region in southern China. Also, the human health risk is high because of the high nitrate concentrations in the groundwater in north-western China. This poses a greater risk to children than to adults in this area[46].

In addition, the damage of costs related to total atmospheric N emissions in China reached 19 billion to 62 billion USD in 2008, which accounted for 0.4% to 1.4% of China's gross domestic product[47].

3 NITROGEN MANAGEMENT PROGRESS

3.1 Progress in N management

Over the past three decades, China's scientific community, leadership and the public have realized the importance of N pollution control. There are many scientific findings regarding N management in systems such as croplands, livestock production and aquaculture. For example, assessments of the effects of management practices, such as the use of enhanced efficiency N fertilizers and optimum N application methods, have been conducted in cropland systems[33,48,49]. A study published in 2017[48] showed that compared with standard management, N practices significantly increased grain yields (Fig. 3) and decreased N losses through leaching, runoff and N emissions. Some researchers have promoted increasing farm size to increase NUE while reducing labor requirements in China[50].

The Chinese Government has also developed a series of programs, projects and regulations to reduce N pollution. Since the 1990s, the Ministry of Agriculture (now known as Ministry of Agriculture and Rural Affairs (MARA)) has implemented a soil testing and fertilizer recommendation (STFR) program to reduce the over-usage of N fertilizer on cereal crops. The central government invested about 2.3 million USD on the program to implement STFR in all 2498 agricultural counties during 2009. In addition, the implementation area consequently increased from 16.7 Mha in 2005 to 66.7 Mha in 2009. The MARA launched a campaign on zero growth of fertilizer and pesticide consumption by 2020 in 2015 to explore ways to develop an environmentally friendly target.

For the water N pollution crisis, there was a declaration on pollution in 2014, and the Chinese Central Government announced major policies in the area of pollution control and remediation. For example, the Chinese Government released an ambitious plan called the Water Pollution Prevention and Control Action Plan (10-Point Water Plan) in April 2015. The plan includes major actions such as controlling and reducing pollutant discharge, promoting the transformation of the economic structure, and strengthening support for science and technology. In particular, the Chinese Government has focused on areas with heavy N pollution, such as the Taihu Lake region. A series of policies for the treatment of N pollution in this region have been implemented since 1995. These policies include a five-year plan and additional management in combination with the actual situation in this region (Fig. 4).

In addition, the Chinese central government has promoted and implemented many national laws, regulations, and policies for air pollution. The Chinese Government set a target of reducing NO_x emissions by 10% during the 12th Five-Year Plan (FYP) period to improve the air quality. However, policies related to N emissions control were not established until the 12th FYP.

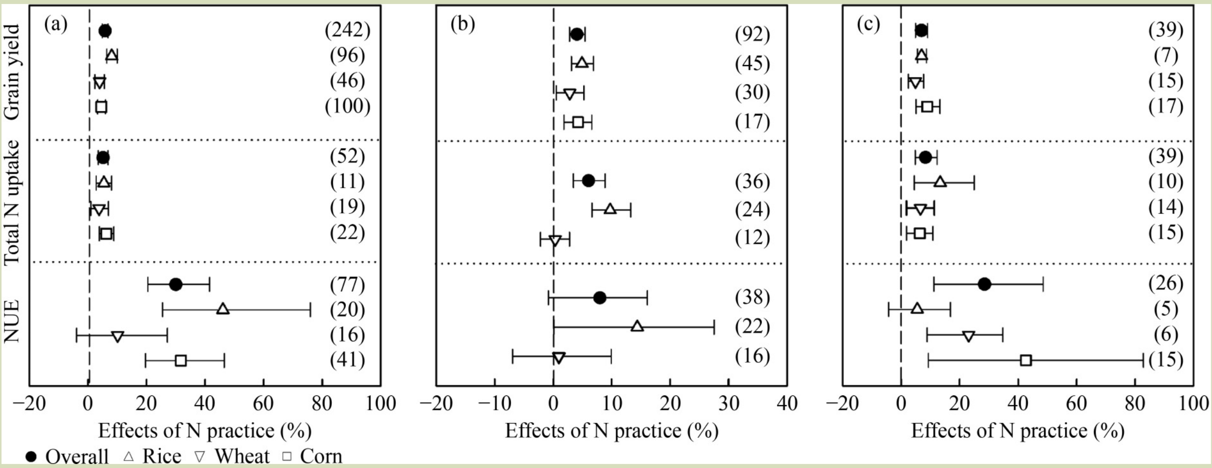

Fig. 3 Changes in grain yield, total aboveground N uptake and NUE by increasing the splitting frequency of fertilizer N application (a), reducing basal N fertilizer proportion (b), and deep placement of N fertilizer (c). Sourced from Xia et al.[48], with permission from John Wiley & Sons Ltd.

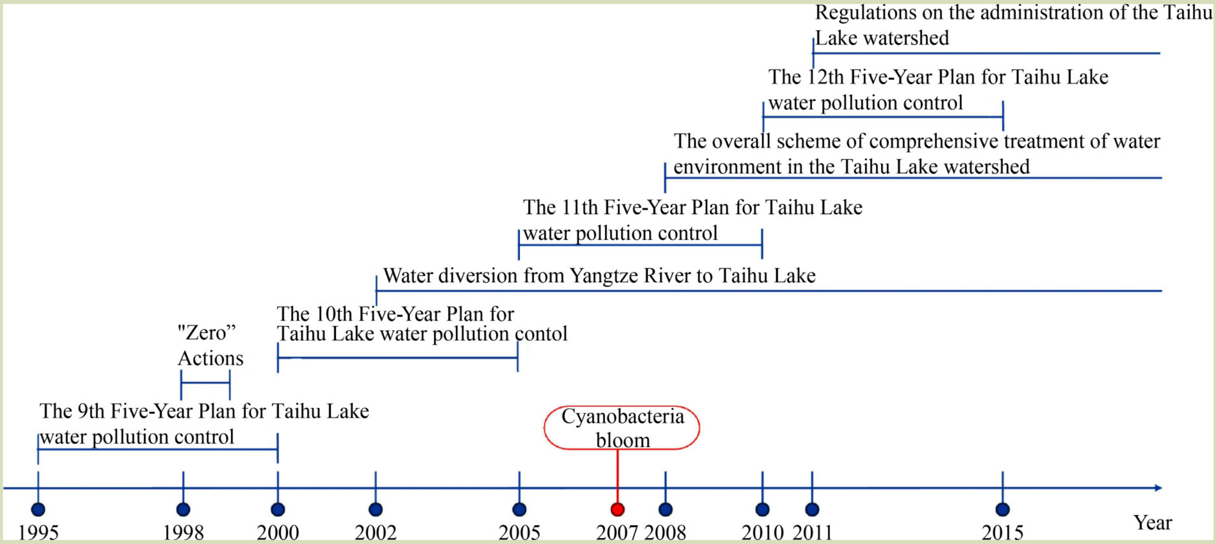

Fig. 4 The policy in nitrogen governance from 1995 to 2015. Modified from Wu et al.[51], with permission from Elsevier.

Since 12th FYP, the Chinese Government has promoted and implemented many national laws, regulations and policies for air pollution reduction (including NO_x and NH_3 emission reductions). For example, the Air Pollution Prevention and Control Action Plan 2013–2017 was launched by the State Council to decouple $PM_{2.5}$. Compared with the control measures for the above pollutants, such as NO_x and nitrite, the control policies for NH_3 emissions before 2018 were considered inadequate in China. With studies on the mechanism of severe haze formation and quantification of NH_3 contributions to $PM_{2.5}$ pollution[52–54], the central government has recognized the importance of NH_3 emission controls and mitigating NH_3 emissions in agriculture was added to the Three-Year Action Plan (2018–2020) for Blue Sky Defense Battle have been implemented[49].

3.2 Successful N management in China

Sustainable N management has significantly positive effects on the environment and social economy. Taking NH_3 and NO_x emission control as an example, one success story was Quzhou, located on the North China Plain, with heavy N fertilizer application. Overuse of N fertilizer is common to pursue high yields in local croplands and leads to intensifying NH_3 emissions and other environmental risks. In 2009, China Agricultural University launched the innovative model of Science and Technology Backyards (STBs) to support farmers on their farms in this region. STBs is an agricultural production support system that linked universities, farmer communities, governments and companies. One of the main objectives of STBs is to increase crop yield and NUE in crop production by analyzing the limiting factors of crop yield as well as the rate of technology in place. By implementing this model, the crop yield increased by 20%, and the application of N fertilizer decreased by 10%[55]. The most successful practice was NH_3 emission mitigation using an innovative urease inhibitor for winter wheat and summer maize production in this region. Compared with standard urea, urease inhibitor-amended urea could reduce 70.5% NH_3 loss while enhancing yield and NUE by 8.7% and 41.3%, respectively[56,57].

Another successful story is the Sheyang Model, which not only acknowledges the structure of agriculture for most rural areas but also provides environmental protection solutions for large-scale farms. To reduce NH_3 mitigation from livestock production in Sheyang, Jiangsu Province, abatement measures were implemented in 2019 following two distinct strategies: (1) improved manure treatment for large farms and (2) collection and central treatment for small farms. The results showed that these measures could reduce the NH_3 emissions by 16%. The cost-benefit analysis demonstrated the advantages of central manure treatment over farm facilities. To control NO_x emissions, air pollution policies have also had positive effects on N deposition. For example, following the implementation of the national NO_x total emission control policy in 2010, national NO_x emissions in China were reduced by about 15% by 2015[58]. As a benefit of NO_x emission reduction in China, the total area and amount of critical load exceedance in East Asia declined by 4.6% and 14.3%, respectively, suggesting great benefits to the natural ecosystem[18].

In addition, with the close attention of the Chinese Government, surface water pollution control has been successful, especially for lakes. For example, over the past two decades, over 50 billion USD has been invested by governments to control water pollution in Taihu Lake through wastewater treatment, waste disposal, ecological remediation, drinking water protection and ecological restoration strategies[51]. By implementing a series of policies and measurements, the annual total TN concentration has decreased continuously since 2006 (Fig. 5). Similarly, several watershed management approaches have been undertaken in Dianchi Lake to improve water quality. By implementing water pollution control and restoration action plans, the water quality of Dianchi Lake rose to class IV for the first time in 30 years in 2018, in which the annual TN concentration decreased from 2.62 $mg \cdot L^{-1}$ in 1998 to 1.46 $mg \cdot L^{-1}$ in 2018.

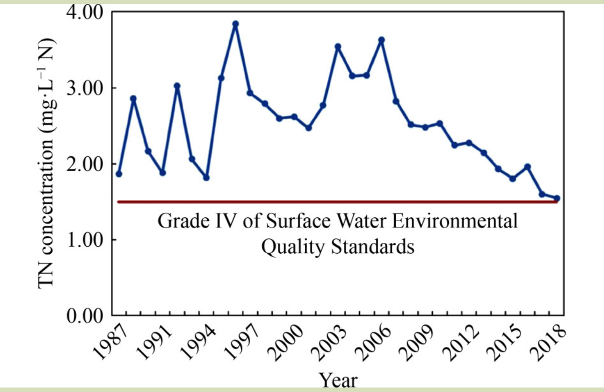

Fig. 5 Annual TN concentration changes in the Taihu Lake.

4 CURRENT BARRIERS TO NITROGEN CONTROL

Despite some successes in N pollution control, balancing the rise in N demand while achieving sustainable development goals still requires overcoming several barriers. First, better quantification and analysis of the N budget and N impacts are needed to improve the understanding of the N cycle and pollution control; for example, because of the complexity of N cycling processes, some possible N flows may not be included in the current N budgets, and some parameters/databases used in the N budget are uncertain. In addition, effects of N on biodiversity loss, groundwater pollution and GHG emissions are not yet fully understood.

Second, technological solutions have been successful in providing reductions in N emissions, such as NH_3. In agriculture, technologies such as the coverage of manure storage and deep placement of mineral fertilizers have contributed to reducing NH_3 emissions. However, some NH_3 emission reduction techniques may incur high costs and increase N_2O emissions. In addition, development of clean, renewable, less energy efficient technologies are important to control air pollution[59]. Therefore, comprehensive N emission reduction measures at low cost are required before implementation[60].

Third, reducing N pollution while simultaneously sustaining economic development requires rational socioeconomic policies and regulations to balance economic growth with pollution control. For example, the farm size is a platform for all technologies to function and implement. Large-scale farming can effectively promote the adoption of advanced technology. In contrast, small farm sizes in China prevent the adoption of innovative technologies, owing to high labor and economic costs[50]. However in China, more than 70% of croplands are managed by farmers with a farm size of less than 0.6 ha[61]. For NO_x, further reduction of NO_x emissions to achieve a continued decline in NO_x requires a change in the energy structure[23]. The above highlights that developing N pollution control strategies should consider socioeconomic factors. Policymakers and stakeholders should consider how N pollution may be abated as cost-effectively as possible.

Fourth, the successful control of N pollution also requires overcoming a range of barriers, such as natural conditions and public participation. For example, water N reduction was achieved in the Taihu Lake region. However, the N concentration in the river was still greater than $1.0\ \mathrm{mg{\cdot}L^{-1}}$. One of the major barriers associated with water pollution is the nature of the conditions in the area. Complex river networks and human activities inhibit the understanding and control of the pollution processes. Most of the N pathways in the river network are blocked and altered by human activities. Additionally, public participation failed to provide an adequate voice of public interests and views regarding N control regulations. Most farmers lack adequate knowledge of management practices, modern production technologies and food safety standards. In addition, they also lack knowledge of environmental practices that benefit biodiversity, soil and water. These barriers suggest that China is facing both challenges and opportunities to reduce N use and losses while maintaining food security. An integrated management framework linking N usage, the environment, health and cost benefits should be established. Public awareness of environmental N pollution issues should be improved. For example, food waste is common in China. 12% of edible food is discarded in Shanghai city[62]. Changes to improve diet and nutrition can add leverage to reduce pressure on food security and mitigate agricultural pollution.

Therefore, combining all strategies, policies, and regulations, such as improving the design of the control and responsibility systems, considering the regional natural conditions and socioeconomic factors, promoting the N cycle and pollution mechanisms, as well as developing optimal environmental tax rates and pollution ecological compensation management systems, may facilitate implementing mitigation technology.

5 FUTURE LOOK

Current N use in China satisfies food and energy demand, while excessive N use results in a cascade of negative impacts. The most important task is to reliability predict future N flows and understand the mechanisms that contribute to these changes. Prediction is difficult given the complexity inherent in N cycling processes and insufficient understanding of the effects of N on biodiversity loss, groundwater pollution and GHG emissions[26]. The best mitigation options are those that address N emissions at the source, which can convert N_2 to N[1]. Therefore, implementation of the following actions are needed. (1) Improving understanding regarding of N cycle. Many processes in the N cycle are poorly understood and some of the major fluxes are subject to significant uncertainty, including the denitrification of nitrogen compounds to molecular nitrogen from terrestrial and marine ecosystems[2]. (2) Increasing the NUE in agricultural systems through the creation of more productive plant cultivars and the use of best available technologies. (3) Minimizing NH_3 emissions by regulatory plans, laws and policies. (4) Improving energy efficiency by developing technologies for reducing emissions, and using alternative energy sources. (5) Improving the quality of wastewater treatment through promotion. (6) Optimizing human dietary habits, maintaining animal-derived food consumption at an optimal level. (7) Fully implementation of government policies, plans and targets based on the collaboration of multiple regions, multiple levels of government. (8) Improving the public awareness of environmental protection issues through medias such as TV channels for public participation in environmental governance, could finally result in a win-win opportunity for N input and sustainable development.

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Compliance with ethics guidelines

Chaopu Ti, Xiaoyuan Yan, Longlong Xia, and Jingwen Huang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any study with human or animal subjects performed by any of the authors.

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